JASPER

The Transporting Capacity of Currents of Water

Civil Engineering

B. S.

1911

UNIV. OF
ILLINOIS
LIBRARY

UNIVERSITY OF ILLINOIS
LIBRARY

Class 1911
Book J311
Volume

THE TRANSPORTING CAPACITY OF CURRENTS OF WATER

BY

THOMAS McLEAN JASPER

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

CIVIL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

PRESENTED JUNE, 1911

1911
J311

1911
J311

UNIVERSITY OF ILLINOIS

COLLEGE OF ENGINEERING

June 1, 1911.

This is to certify that the thesis prepared in the Department of Theoretical and Applied Mechanics by THOMAS MCLEAN JASPER entitled The Transporting Capacity of Currents of Water is approved by me as fulfilling this part of the requirements for the degree of Bachelor of Science in Civil Engineering.

M. L. Enger
A N Talbot
Instructors in Charge.

Approved:

A N Talbot
Professor of Municipal and Sanitary Engineering
In charge of Theoretical and Applied Mechanics.

Approved:

Ira O. Baker.
Professor of Civil Engineering.

197650

UIUC

TABLE OF CONTENTS.

	Page
Introduction	1
Preliminary Observations	2
Planning of Work	3
Logarithmic Plotting	4
Description of Apparatus	5
Preliminary Work	10
Experiments:	
1. Relation between Velocity of Balls and Velocity ofMaterial	13
2. Relation Between Velocity of Balls and Diameter of Balls	21
3. Relation Between the Velocity of Balls and Their SpecificGravity	29
Development of Formula	31
Constants (K)	36
Conclusion	37

Digitized by the Internet Archive
in 2013

http://archive.org/details/transportingcapa00jasp

TABLE OF FIGURES.

	Page
Figure I Diagram of Pitot Tube	8
Figure II RatingCurves for the Pitot Tube	9
Figure III Curves Showing Relation between Velocity of Ball andVelocity of Water, Rolling on Glass	17
Figure IV Curves Showing Relation between Velocity of Ball and Velocity of Water, Rolling on Wood	20
Figure V Curves Showing Relation between Velocity of Ball and Diameter of Ball, Rolling on Glass	25
Figure VI Curves Showing Relation between Velocity of Ball and Diameter of Ball, rolling on Wood	28
Figure VII Curves Showing Relation between Velocity ofBall and Specific Gravity of Ball	30

THE TRANSPORTING CAPACITY OF CURRENTS OF WATER.

Introduction.

The subject for investigation was suggested by the fact that little information is available concerning the action of currents of water in transporting sand and silt. It is well known that large deposits have been formed along the banks and at the mouths of some large rivers; and that cities which were once at the mouth are in some instances several miles inland. The sources of danger offered by this fact are many, both to those living along their banks, and to navigators of those rivers. Sand banks are formed very rapidly, and in some instances the course of a river has been changed at very little notice. Bridges whose piers have materially narrowed the bed of a river have sometimes been undermined and have failed, due to the lack of knowledge concerning the action of currents of water, and the relation between the velocity of the water to the amount of material carried by it.

This was brought to the notice of the writer in the fall of 1910 at Spokane, Washington. The Washington Street Bridge, a concrete structure with piers 9 feet thick (perpendicular to the flow of the stream) had holes and pockets 3 feet under one pier and 4 1/2 feet under the other, dug out by the action of the water. The bridge at this time had 2 1/2 years use. The velocity of the river at this point is very large. On the Monroe Street Bridge, Spokane, Washington, the large abutment under the main pier for the 281 foot arch (concrete structure) was under-

mined 6 feet in as many months. The velocity of the water here was great, due to the tail race of a large hydraulic power plant. These instances show that proper precaution had not been taken to deal with abnormal cases, due no doubt to the fact that little was known as to the action of water as an agent of destruction.

That there are critical velocities at which the materials carried by the water are deposited, or are taken up again seems to be the usual theory, but experimental data with materials not in suspension seem to show that the velocities at which materials are deposited are exceedingly small, providing the surfaces in contact offer little resistance.

Materials of specific gravity very little higher than that of water are kept in suspension, partly by the viscosity of the water and partly due to internal currents.

The writer has endeavored to find some relation between the velocity of the water and the material carried by it.

Preliminary Observations.

The first trials made were to watch the behavior of sand of fairly uniform size on being introduced into a stream of flowing water and to see if the repitition of the experiment gave comparable results. The results seemed to show that there was a definite relation between the velocity of the sand and the velocity of the water. These experiments were repeated with sand of different sizes and the results seemed to show that the size of the particle had something to do with the relative velocity of the sand. Difference in weight of particles of the same size also has something to do with the relative velocity of the particle.

From these investigations it was readily seen that several variables would have to be dealt with. The observations seemed to point to the fact that each variable varied in an exponential manner.

Planning of the Work.

From the foregoing conclusions it was decided to deal with only two variables at a time. The results were then taken and plotted on logarithmic cross section paper and the resulting curve analysed in order to find out the relation between the variables. The variables were, velocity of water, size of particle, weight of particle, and velocity of particle.

As has already been explained it was decided to work with four variables which seemed to be the logical outcome of the preliminary observation. In order to have a uniformity of conditions as to the shape, spheres were used, the sizes ranging from 0.1 inches to 1.3 inches. Variation of specific gravity was obtained by using lead, steel, glass and gravel. The bottom of the channel was level, glass and wood being used as the surface in contact. The method of determining the velocity of the spheres or balls as they will be called, was to observe the time required to roll them a certain distance in the water. The method of obtaining the velocity of the water at the height of the center of the rolling ball, was to use a pitot tube which had been previously rated, and which will be described more fully in the following description. River gravel and sand were also used, to see whether the relation found, held for material with other than smooth surfaces and definite shapes.

Logarithmic Plotting.

An explanation of the use of logarithmic plottings to determine the exponents and coefficients of an exponential equation may be useful.

It is the particular property of logarithmic section paper that for all relationships which involve multiplication, division, raising to powers or extraction of roots, the lines representing them are straight. It may be readily proved as follows. Any such relationship may be represented by an equation of the form

$$y=m(x)^n$$

This equation may be expressed logarithmically as

$$\log y = \log m + n \log x.$$

If this equation was plotted on ordinary cross section paper, with log y, log m and n log x having numerical values, the result would be a straight line which might be written in the form

$$y = ax + b.$$

Since y and x are variables the slope of the curve represented by this equation will be a. The process as explained so far has been to take the logarithms of values and plot them on ordinary cross section paper. Instead of taking the logarithms of values and plotting them on ordinary cross section paper we may take the numbers and plot them on logarithmic section paper and obtain the same result. The result will be a straight line whose slope is a.

For experimental data in which we wish to find the exponential relation between the variables, the properties of logarithmic plottings are readily applicable. The points representing the experimental data may be plotted and a line joining them drawn

If the curve approaches very nearly a straight line it may be assumed that the variables have an exponential relation which can be expressed by the equation

$$y = m(x)^n$$

From the slope of the curve may be obtained n. The value of m may be computed from the logarithmic relation by taking the exponential values of y and x in the equation

$$\log y = \log m + n \log x.$$

or

$$\log m = \log y - n \log x.$$

If possible the value of x should be chosen as 1. The equation then becomes

$$\log m = \log y.$$

$$m = y$$

and the value of m can be read directly from the intersection of the curve representing the experimental plottings, with the value of the y axis corresponding to x = 1.

Description of Apparatus.

The level surface was obtained in a flume 20 feet long, 14 inches wide and 9 inches deep. In order to have a smooth surface a long plate of glass was placed on the bottom of the flume, the other surface used being the planed wood bottom of the flume. Water was introduced into the flume through a weir box and two sets of baffles to insure uniform flow. In order to obtain a ready means of adjusting the amount of water for the experiments, and to keep the flow from fluctuating rapidly, a vertical jet was used. The height of the jet of water being an

indicator of the discharge through the orifice. By this means the desired quantity could be readily and fairly accurately adjusted. The actual velocity of the water in the flume was measured by the use of the pitot tube before mentioned.

The pitot tube measures the velocity head of a current of water by means of a tube bent at right angles, with its mouth placed up stream. The water will be forced into this tube due to its velocity, and the height it will rise in the tube will indicate the velocity head of the stream. With small velocities it is desirable to magnify readings of the velocity head. For this reason a pitot tube was devised which used liquids of different specific gravity as a means to magnify the readings of the head.

The pitot tube used see (Fig. 1.) consists of a bent glass tube A. with a drawn out and finely ground point, a straight tube B, and a differential gauge consisting of a U tube C, with flexible tubing, stop cocks and connections as shown. Into the tube C was introduced a liquid of greater specific gravity than water and which was insoluble in water. Carbon-tetra chloride ($C\ CL_4$) and benzole ($C_6\ H_6$) were mixed in varying proportions allowing specific gravities to range from 1.0 to 1.6.

The underlying principle may be explained by referring to Fig. 1. Taking a section through tube C at Y it is readily seen that the pressures in both arms are equal. Taking another section at X the difference of pressure will be equal to the difference in the weight of the liquid in the two arms of tube C. between sections X and Y. Supposing in the upstream arm of the tube the section between X and Y is filled with carbon-tetra chloride and

benzole and in the down stream arm it is water, the difference will be equal to h times the specific gravity of carbon-tetra chloride and benzole minus h times the specific gravity of water. Letting specific gravity of carbon-tetra chloride and benzole be represented by S the difference will be

$$h(S - 1)$$

It can be readily seen that the actual velocity head will be

$$h(S - 1)$$

while the difference shown by the column will be h. Since S may be made to approach 1, the difference between the specific gravity of benzole and carbon-tetra chloride mixed and the water may be made as small as may be desired, and therefore a very small velocity head may be made to show a large reading of h. In this way it is possible to measure a very small velocity head. This furnishes an accurate method of measuring the velocity of the water below the surface provided the apparatus is accurately rated, and large velocities can also be measured by increasing the specific gravity of the liquid in the U tube.

A curve similar to the one shown (Fig. 2.) but on a larger scale was used on which the head in feet and velocity in feet per second were plotted as absissae and ordinates, respectively, for all the different mixtures used in tube C in the experiment. This simply increased the speed at which experiments could be performed and eliminated a large source of error in the results.

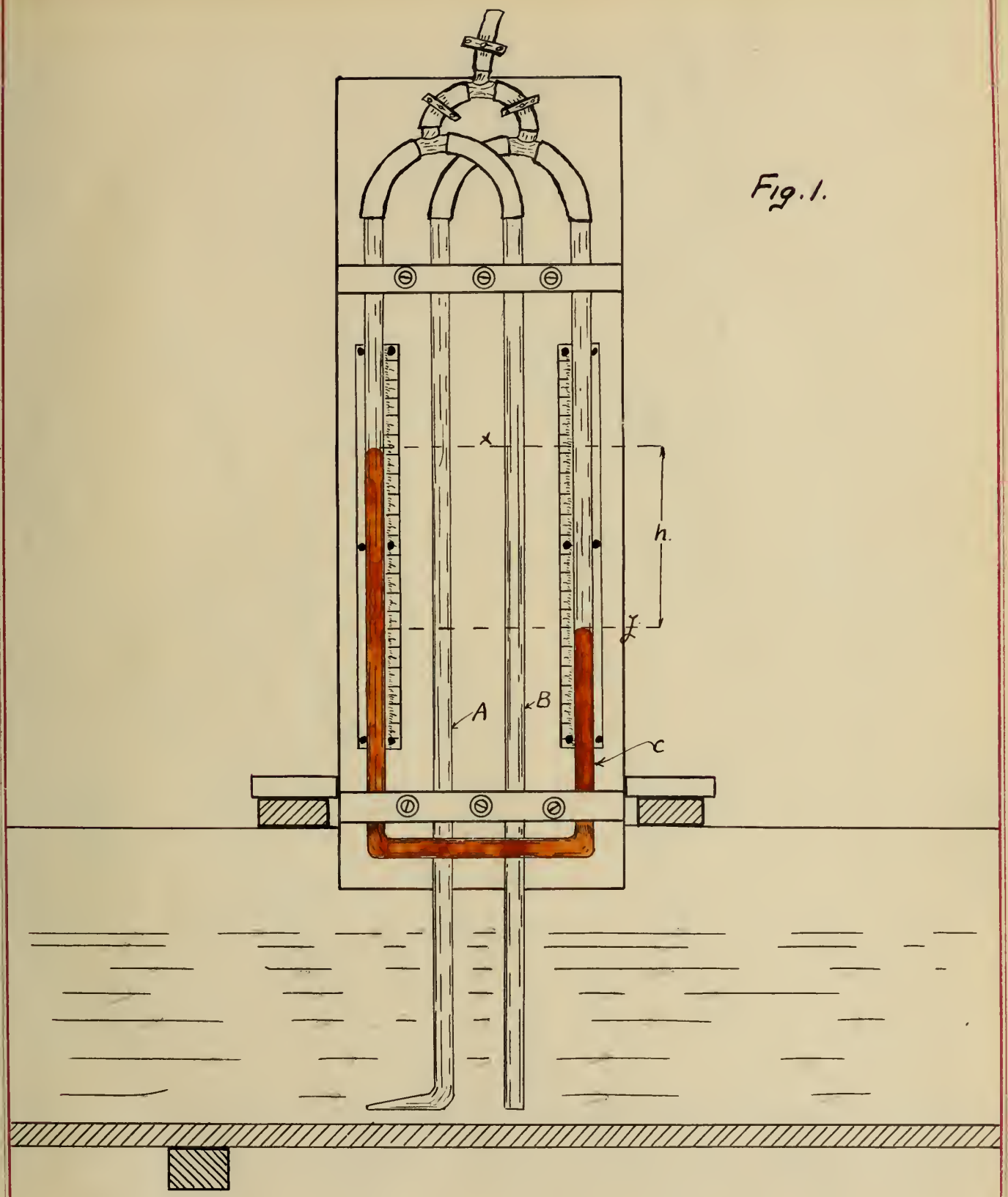


Fig. 1.

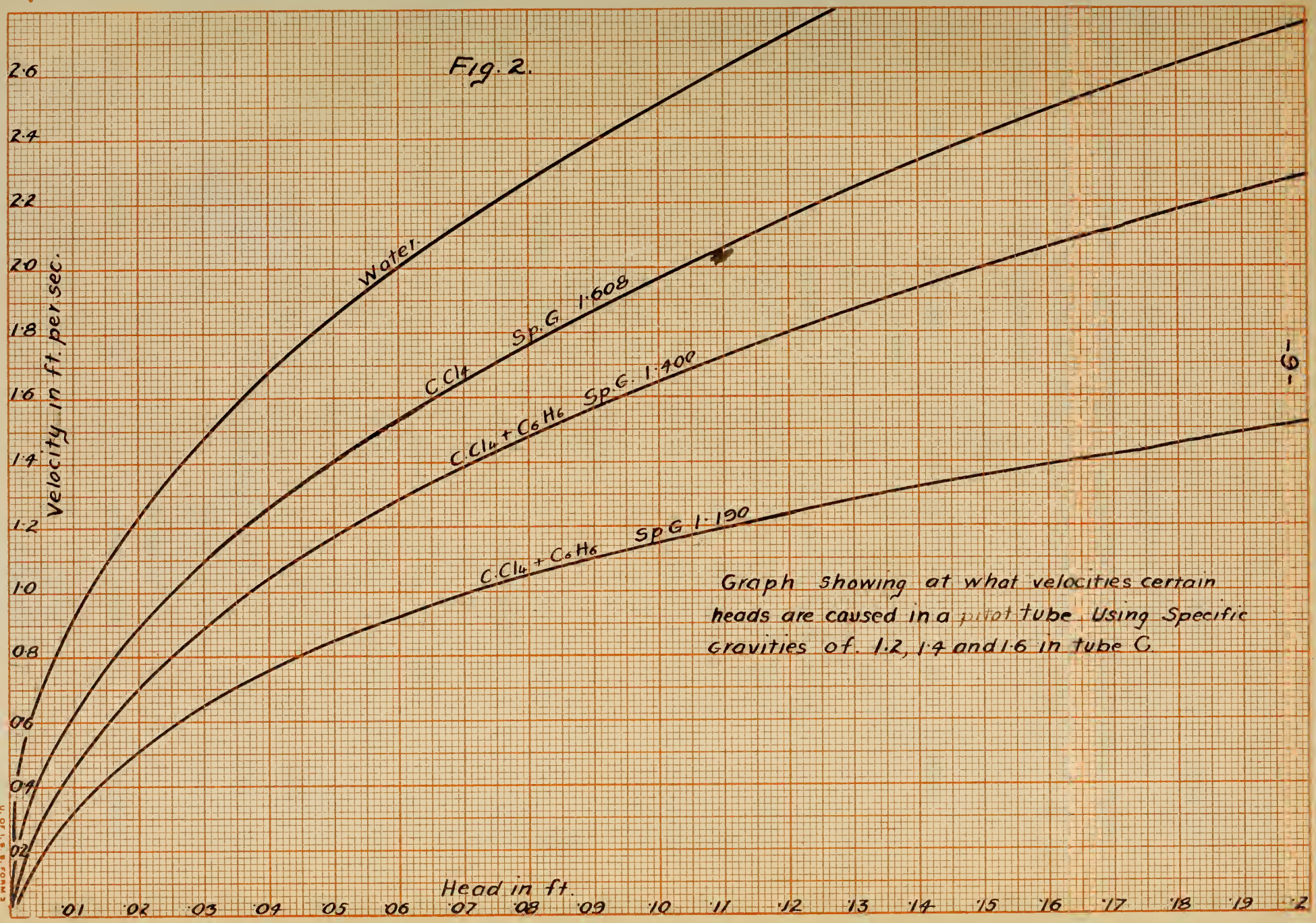


Fig. 2.
Velocity in ft. per sec.
2·6
2·4
2·2
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
Water.
C Cl4 Sp. G. 1·608
C Cl4 + C6 H6 Sp. G. 1·400
C Cl4 + C6 H6 Sp G 1·190
Graph showing at what velocities certain heads are caused in a pitot tube. Using Specific Gravities of 1·2, 1·4 and 1·6 in tube C.
Head in ft.
·01 ·02 ·03 ·04 ·05 ·06 ·07 ·08 ·09 ·10 ·11 ·12 ·13 ·14 ·15 ·16 ·17 ·18 ·19 ·2

Preliminary Work.

Several preliminary experiments were necessary in order to arrive at an accurate rating for the pitot tube, and also to obtain the specific gravity for the different materials. The method of obtaining the rating for the pitot tube, that is to determine C in the formula

$$V = C\sqrt{2gh}$$

was as follows. The mouths of tubes A and B (Fig. 1.) were brought as near as possible the surface of the water in the flume without allowing air to be introduced through them. Floats were then used on the surface of the water and the time taken in conjunction with the distance over which the floats passed. This gave a means of determining the surface velocity (Vw) of the water. The head in the tube was read and the velocity calculated from this head by the formula

$$Vt = \sqrt{2gh}.$$

The actual velocity of course was given by the float. Then $\frac{Vt}{Vw}$ would give the constant C, necessary to be used in order to arrive at a correct value of the velocity when using the pitot tube.

The specific gravities of lead, steel and glass were taken from Van Nostrands Chemical Handbook. That for sand was obtained as follows: The weight in grams of a graduated cylinder, partly filled with water was taken. The amount of water was noted in cubic centimeters. The dried sand or gravel was then introduced into the cylinder with the water. The increase in weight of the cylinder and materials was divided by the cubic centimeter apparent increase in volume. As an average of five experiments a specific gravity of 2.74 was obtained for the sand and gravel.

The specific gravity of the liquid used in the pitot tube was obtained by a hydrometer, and specific gravities of 1, 1.2, 1.4, and 1.6 were obtainedfor the subsequent experiments.

The nomenclature used for the rating of the pitot tube was as follows.

Ht.	Head in tube c. (ft)
Vt.	Velocity shown by curve for specific used in tube c. (ft.per sec)
Vw.	Velocity of water = C Vt. (ft. per sec.)
L.	Distance through which floats were timed.(ft)
T.	Time. (seconds)
C.	Constant in the formula $Vw = C\sqrt{2gh}$.

Data.

Specific gravity of liquid used in U tube = 1.6. ($C\ Cl_4$)

Vw.	Ht.	Vt.	L.	T.	C.
.77	.0198	.82	17	22.0	.94
.69	.0133	.72	17	24.6	.96
1.20	.0440	1.31	17	14.8	.92
.77	.0165	.80	17	21.2	.96

Each of the numbers in columns Vw, Ht are an average of 10 readings.

Average $\frac{Vw}{Vt} = C = .94$ which was used as the rating for the pitot tube throughout.

Experiments.

In planning the experiments it was decided to use the four variables suggested from the preliminary observations and since the relative velocity of the materials was sought with reference to the investigation, that variable was used in each group of variables. Therefore the grouping will be in the following order:

1st. group. Relation between the velocity of balls and velocity of material.

2nd. group. Relation between the velocity of balls and size of balls.

3rd. group. Relation between the velocity of balls and specific gravity of balls.

The variables for each group were plotted on logarithmic paper and the relations obtained as explained in the description of logarithmic plotting.

Nomenclature.

Vt. Velocity taken from curve (fig. 2.) due to reading Ht. (ft. per sec.)

Vw. Velocity of water = C Vt. = .94 Vt. (ft. per sec.)

Ht. Head shown in pitot tube.(feet)

Db. Diameter of ball. (inches)

Vb. Velocity of ball. (feet per sec.)

L. Distance that balls were rolled. (feet)

T. Time. (seconds)

Sp. G. Specific gravity. (water units)

Data assumed. Specific gravity of lead 11.3, steel, 7.7, and glass 2.7. The diameter of the balls were obtained to the

nearest hundreth of an inch. Some of the balls used were of small diameter so as to approximate as nearly as possible the conditions in a stream. Each head shown in the Ht. column, velocity of ball shown in Vb column, and time shown in T column for their respective groups are an average of 10 readings.

Group I. Relation between the velocity of balls and velocity of water.

This group of experiments is tabulated on the following sheets, and from these tabulations, logarithmic plottings obtained. From an examination of the plottings the following relation is found (explanation given under logarithmic plotting):

$$Vb = (Vw)^{\frac{1}{3}} \cdot \overline{C}_I .$$

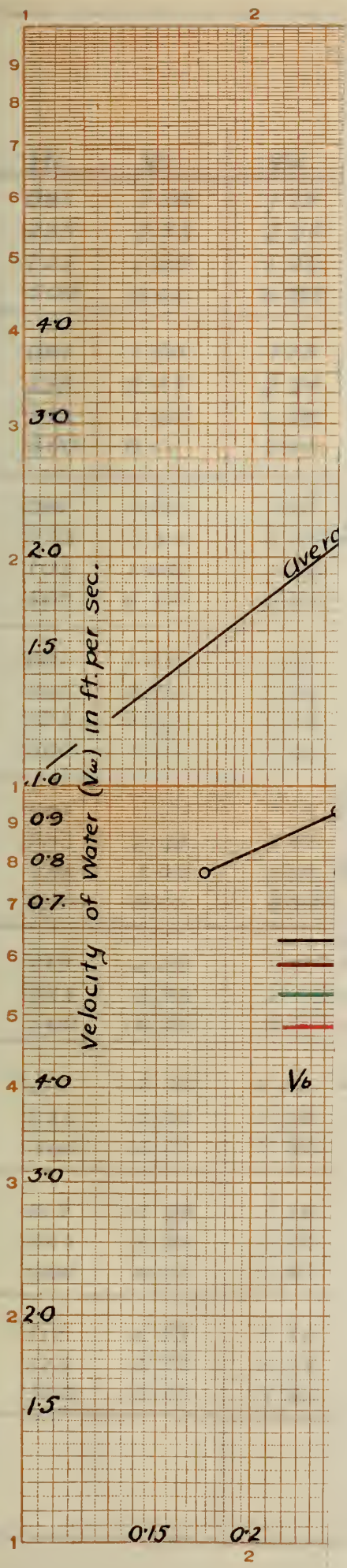
$\overline{C}_I$ being a constant, which in Group I shall satisfy the equation.

The group is subdivided into experiments in which the surface in contact is glass and wood. The purpose of this is to eventually arrive at the division of the constant K used in the general formula and to give coefficients for the different materials used.

Ht	Vt	Vw	Db	L	T	Vb	Sp.G in tube C.	Sp.G. of material
·060	1·52	1·43	·3750	5·00	7·16	·700	1·6	
·082	1·79	1·68	"	5·00	6·00	·833	1·6	
·073	·96	·90	"	5·00	13·5	·370	1·2	
·049	·80	·75	"	4·48	15·7	·285	1·2	
·210	2·32	2·18	"	5·00	4·25	1·18	1·4	
·060	1·52	1·43	·3125	5·00	7·54	·665	1·6	Steel Rolling on Glass. → Sp.G 7.7.
·082	1·79	1·68	"	5·00	6·03	·805	1·6	
·073	·96	·90	"	5·00	14·15	·353	1·2	
·049	·80	·75	"	4·48	15·90	·282	1·2	
·210	2·32	2·18	"	5·00	4·47	1·12	1·4	
·060	1·52	1·43	·2810	5·00	7·85	·636	1·6	
·082	1·79	1·68	"	5·00	6·5	·770	1·6	
·073	·96	·90	"	5·00	14·9	·334	1·2	
·049	·80	·75	"	4·48	17·0	·264	1·2	
·210	2·32	2·18	"	5·00	4·63	1·08	1·4	
·060	1·52	1·43	·2500	5·00	8·03	·624	1·6	
·082	1·79	1·68	"	5·00	7·0	·74	1·6	
·073	·96	·90	"	5·00	15·1	·33	1·2	
·049	·80	·75	"	4·48	17·1	·26	1·2	
·210	2·32	2·18	"	5·00	4·56	?	1·4	
·060	1·52	1·43	·1885	5·00	8·15	·613	1·6	
·082	1·79	1·68	"	5·00	7·50	·666	1·6	
·073	·96	·90	"	5·00	17·0	·294	1·2	
·049	·80	·75	"	4·48	20·9	·215	1·2	
·210	2·32	2·18	"	5·00	4·78	1·04	1·4	
·060	1·52	1·43	·1258	5·00	9·1	·55	1·6	
·082	1·79	1·68	"	5·00	8·4	·59	1·6	
·073	·96	·90	"	5·00	19·6	·26	1·2	
·049	·80	·75	"	4·48	28·5	·16	1·2	
·210	2·32	2·18	"	5·00	5·5	·91	1·4.	
·186	2·24	2·11	1·31	5·00	3·00	1·67	1·6	Glass rolling on Glass. Sp.G 2·7.
·031	1·11	1·04	"	5·00	8·25	·61	1·6	
·064	1·57	1·48	"	5·00	5·25	·95	1·6	
·09	1·87	1·76	"	5·00	4·29	1·17	1·6	

Ht	Vt	Vw	Db	L	T	Vb	Sp. G in tube. C.	Remarks.
·186	2·24	2·11	·96	5·00	3·44	1·45	1·6	Glass rolling on Glass Sp. G 2·7.
·031	1·11	1·04	"	"	8·52	·59	"	
·064	1·57	1·48	"	"	5·5	·91	"	
·09	1·87	1·76	"	"	4·75	1·05	"	
·186	2·24	2·11	·76	5·00	3·80	1·42	1·6	
·031	1·11	1·04	"	"	9·09	·55	"	
·064	1·57	1·48	"	"	5·7	·88	"	
·09	1·87	1·76	"	"	4·95	1·01	"	
·186	2·24	2·11	·64	5·00	3·67	1·36	1·6	
·031	1·11	1·04	"	"	9·40	·53	"	
·064	1·57	1·48	"	"	5·75	·87	"	
·09	1·87	1·76	"	"	4·80	1·04	"	
·186	2·24	2·11	1·01	5·00	3·31	1·51	1·6	
·031	1·11	1·04	"	"	8·60	·58	"	
·064	1·57	1·48	"	"	5·4	·92	"	
·09	1·87	1·76	"	"	4·67	1·07	"	
·069	1·38	1·30	1·3	4·00	5·60	·715	1·4	Lead rolling on Glass Sp. G 11·3
·108	1·72	1·60	"	"	4·80	·83	"	
·130	1·88	1·77	"	"	4·50	·89	"	
·262	2·63	2·47	"	"	2·96	1·35	"	
·069	1·38	1·30	1·0	4·00	6·40	·63	1·4	
·108	1·72	1·60	"	"	5·00	·80	"	
·130	1·88	1·77	"	"	4·62	·86	"	
·262	2·63	2·47	"	"	3·25	1·23	"	
·069	1·38	1·30	·86	4·00	7·07	·56	1·4	
·108	1·72	1·60	"	"	5·17	·77	"	
·130	1·88	1·77	"	"	4·80	·83	"	
·262	2·63	2·47	"	"	3·33	1·20	"	
·069	1·38	1·30	·82	4·00	7·00	·75	1·4	
·108	1·72	1·60	"	"	5·17	·77	"	
·130	1·88	1·77	"	"	4·96	·80	"	
·262	2·63	2·47	"	"	3·41	1·17	"	
·069	1·38	1·30	·64	4·00	7·40	·54	1·4	
·108	1·72	1·60	"	"	5·71	·70	"	
·130	1·88	1·77	"	"	5·13	·78	"	
·262	2·63	2·47	"	"	3·91	1·02	"	

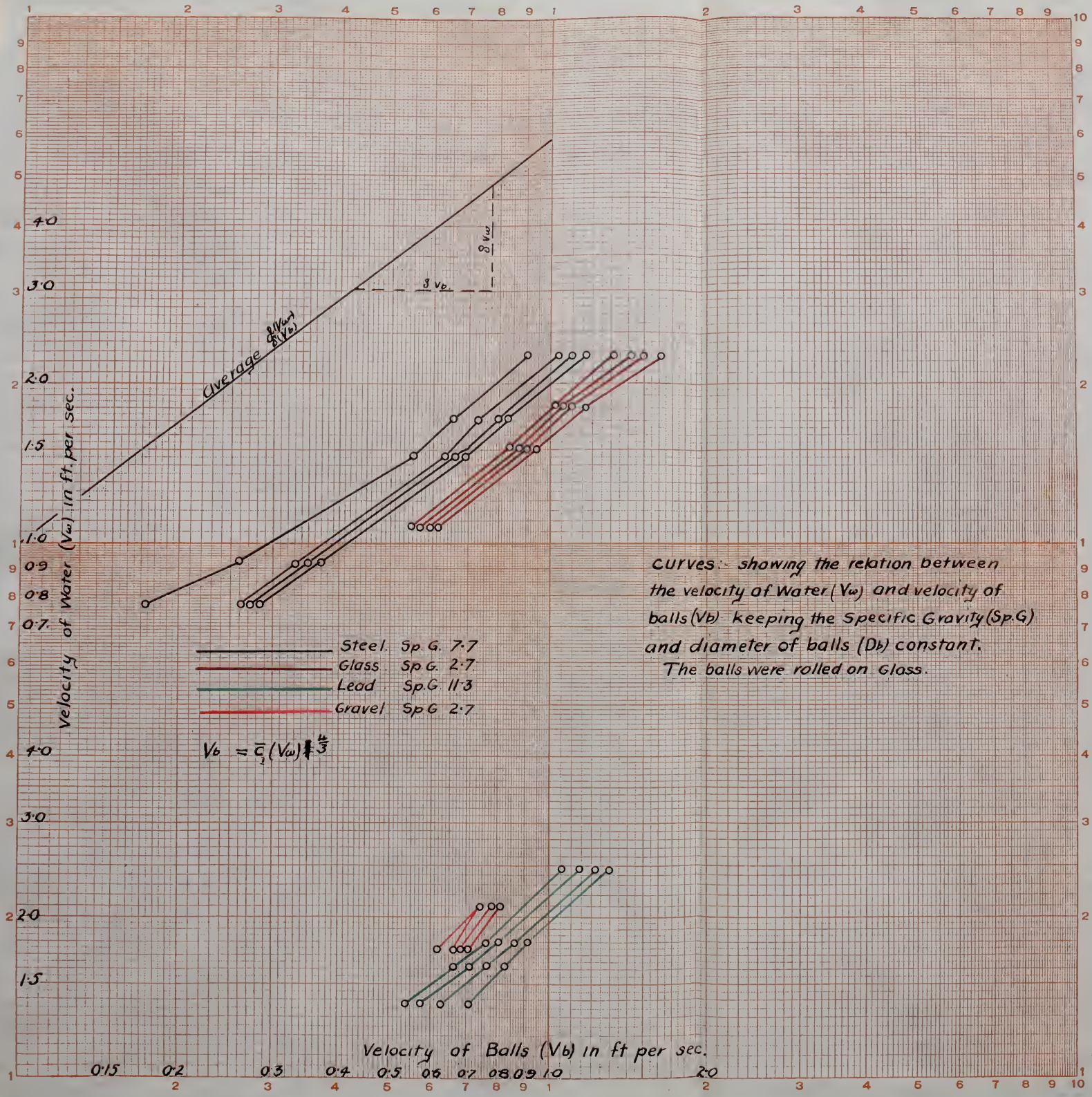
Ht	Vt	Vw	Db	L	T	Vb	Sp G in tube C.	Remarks
·122	1·82	1·74	·625	5	7·10	·705	1·4	Gravel on Glass Sp.G. 2·7.
·185	2·23	2·10	"	"	6·00	·822	"	
·122	1·82	1·74	·437	5	7·37	·680	1·4	
·185	2·23	2·10	"	"	6·15	·800	"	
·122	1·82	1·74	·338	5	7·40	·675	1·4	
·185	2·23	2·10	"	"	6·66	·750	"	
·122	1·82	1·74	·230	5	7·94	·630	1·4	
·185	2·23	2·10	"	"	6·60	·750	"	



arks.

Sp. G 2·7.

Sp. G 7·7

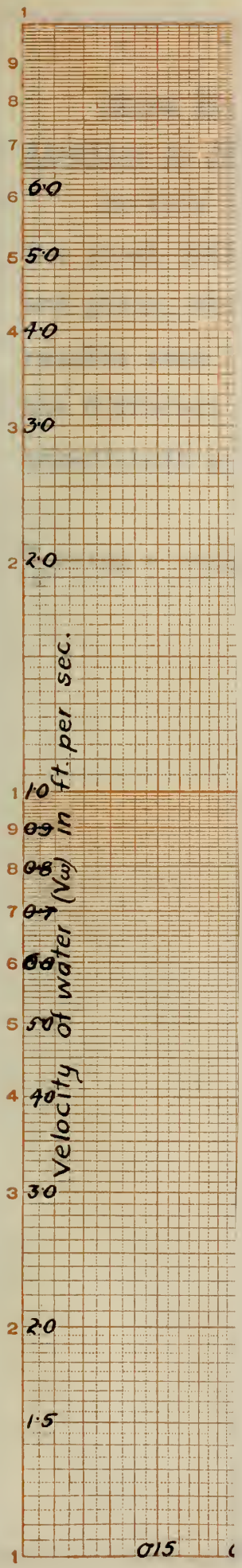


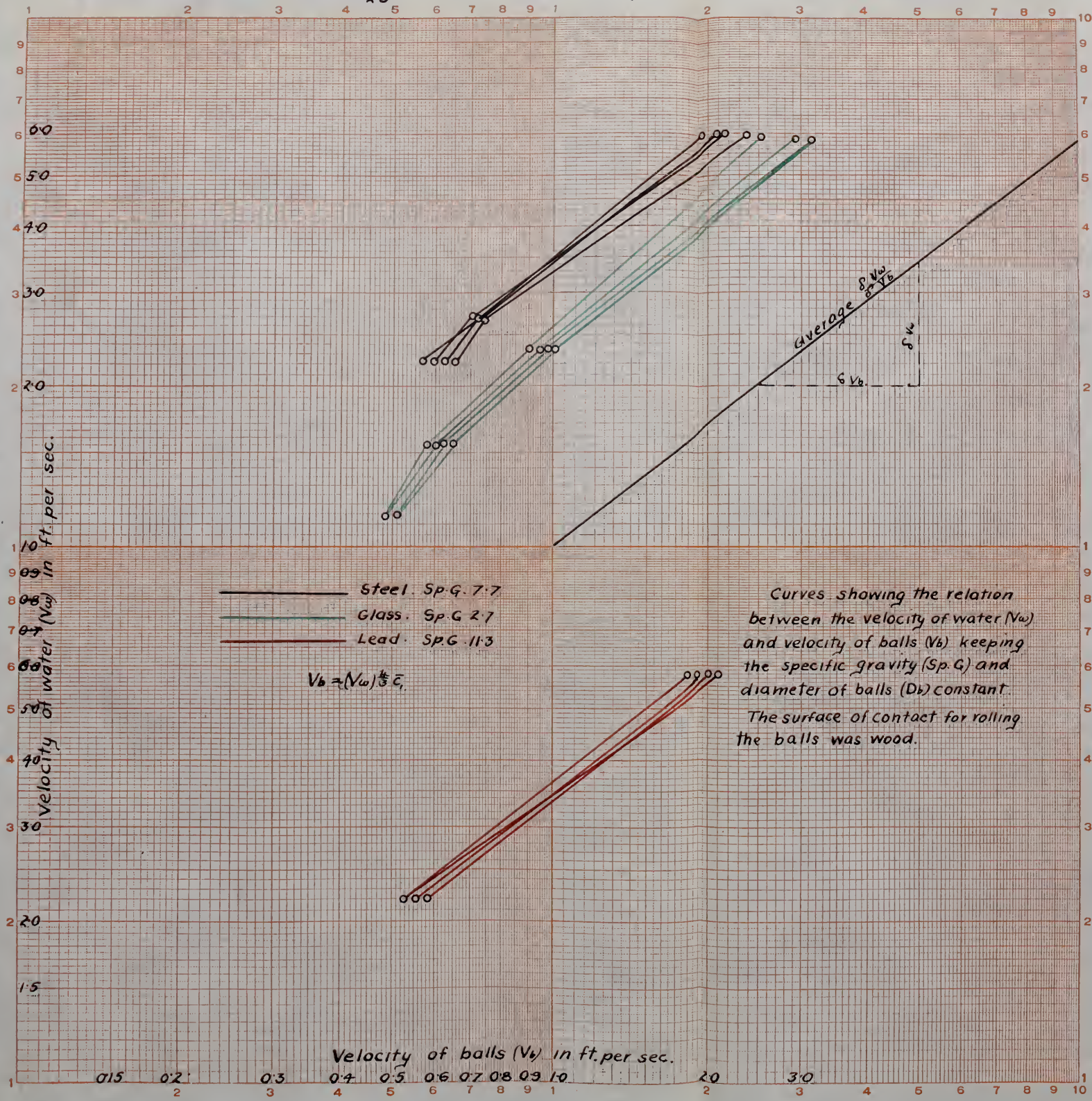
Curves: showing the relation between the velocity of Water (V_ω) and velocity of balls (V_b) keeping the Specific Gravity (Sp. G) and diameter of balls (D_b) constant.
The balls were rolled on Glass.

COPYRIGHT 1908. J. NORMAN JENSEN, CIVIL ENGINEER. CHICAGO, ILL., U. S. A.

Ht	Vt	Vw	Db	L	T	Vb	Sp. G. in tube C.	Remarks
·081	1·20	1·13	1·31	5	10·03	·50	1·2	Glass rolling on wood Sp. G 2·7
·235	2·44	2·34	"	"	5·00	1·00	1·4	
·103	1·66	1·56	"	"	7·90	·63	1·4	
·500	6·21	5·85	"	"	1·60	3·12	1·6	
·081	1·20	1·13	1·01	5	9·90	·51	1·2	
·235	2·44	2·34	"	"	5·30	·94	1·4	
·103	1·66	1·56	"	"	8·03	·62	1·4	
·500	6·21	5·85	"	"	1·70	2·94	1·6	
·081	1·20	1·13	·96	5	10·00	·50	1·2	
·235	2·44	2·34	"	"	5·20	·96	1·4	
·103	1·66	1·56	"	"	8·30	·60	1·4	
·500	6·21	5·85	"	"	1·70	2·94	1·6	
·081	1·20	1·13	·76	5	10·50	·48	1·2	
·235	2·44	2·34	"	"	5·40	·93	1·4	
·103	1·66	1·56	"	"	8·50	·59	1·4	
·500	6·21	5·85	"	"	1·80	2·78	1·6	
·081	1·20	1·13	·64	5	10·50	·48	1·2	
·235	2·44	2·44	"	"	5·60	·89	1·4	
·105	1·66	1·66	"	"	8·80	·57	1·4	
·500	6·21	5·86	"	"	2·00	2·50	1·6	
·219	2·39	2·26	·3750	5	8·30	·60	1·4	Steel rolling on wood Sp. G 7·7
·325	2·92	2·74	"	"	7·20	·70	1·4	
·500	6·21	5·85	"	"	2·40	2·38	1·6	
·219	2·39	2·26	·3125	5	8·50	·59	1·4	
·325	2·92	2·74	"	"	7·10	·71	1·4	
·500	6·21	5·85	"	"	2·50	2·14	1·6	
·219	2·39	2·26	·2500	5	8·40	·60	1·4	
·325	2·92	2·74	"	"	7·20	·70	1·4	
·500	6·21	5·85	"	"	2·60	2·08	1·6	
·219	2·39	2·26	·1258	5	9·80	·51	1·4	
·325	2·92	2·74	"	"	8·20	·61	1·4	
·500	6·21	5·85.	"	"	2·70	1·87	1·6	

Ht	Vt	Vw	Db	L	T	Vb	Sp.G. in Tube C.	Remarks
·218	2·39	2·26	1·0	5	9·8	·51	1·4	Lead rolling on wood Sp.G. 11.3
·600	6·21	5·85	"	"	2·4	2·10	1·6	
·218	2·39	2·26	·86	5	9·7	·52	1·4	
·600	6·21	5·85	"	"	2·6	1·92	1·6	
·218	2·39	2·26	·82	5	9·3	·54	1·4	
·600	6·21	5·85	"	"	2·7	1·85	1·6	
·218	2·39	2·26	·64	5	9·0	·55	1·4	
·600	6·21	5·85	"	"	2·8	1·78	1·6	


Velocity of water (V_w) in ft. per sec.
6·0
5·0
4·0
3·0
2·0
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
1·5
0·15



COPYRIGHT 1906. J. NORMAN JENSEN, CIVIL ENGINEER, CHICAGO, ILL., U. S. A.

Group II. Relation between the velocity of balls and diameter of balls.

In this group it will be noted that the average diameter of the steel balls used were very much less than that used for lead and glass, which fact would seem to be unfavorable, yet the results seem to indicate that the same relation exists between the different kinds of materials. From an examination of the logarithmic plottings the following relation is found:

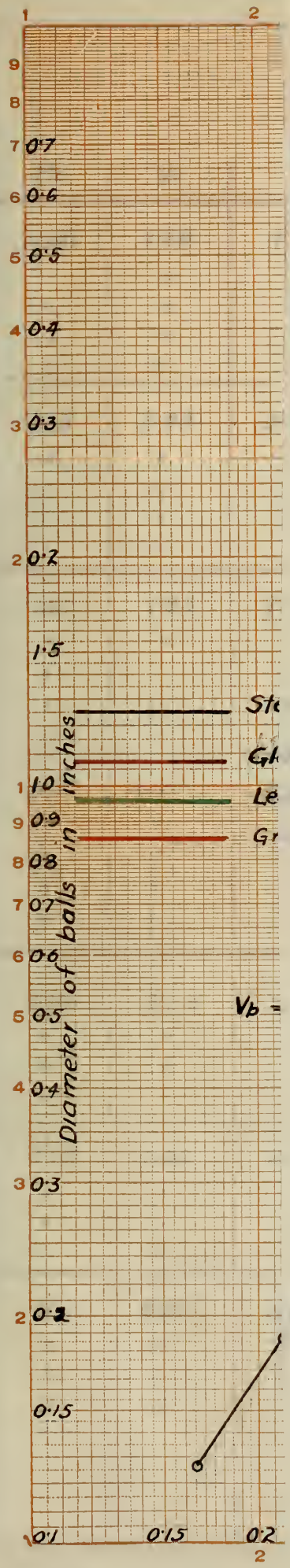
$$Vb = (Db)^{\frac{1}{3}} \overline{C}_{II}$$

$\overline{C}_{II}$ being a constant.

Ht	Vt	Vw.	Db	L	T	Vb	Sp.G in tube C.	Remarks.
·060	1·52	1·43	·3750	5·00	7·16	·700	1·6	Steel. Sp.G. 7·7 rolling on Glass.
"	"	"	·3125	"	7·54	·665	"	
"	"	"	·2810	"	7·85	·636	"	
"	"	"	·2500	"	8·03	·624	"	
"	"	"	·1885	"	8·15	·613	"	
"	"	"	·1258	"	9·10	·550	"	
·082	1·79	1·68	·3750	5·00	6·00	·833	1·6	
"	"	"	·3125	"	6·03	·805	"	
"	"	"	·2810	"	6·50	·770	"	
"	"	"	·2500	"	7·00	·740	"	
"	"	"	·1885	"	7·50	·666	"	
"	"	"	·1258	"	8·40	·590	"	
·073	·96	·90	·3750	5·00	13·50	·370	1·2	
"	"	"	·3125	"	19·15	·353	"	
"	"	"	·2810	"	14·96	·334	"	
"	"	"	·2500	"	15·10	·330	"	
"	"	"	·1885	"	17·00	·294	"	
"	"	"	·1258	"	19·60	·260	"	
·049	·80	·75	·3750	4·48	15·70	·285	1·2	
"	"	"	·3125	"	15·90	·282	"	
"	"	"	·2810	"	17·00	·264	"	
"	"	"	·2500	"	17·10	·260	"	
"	"	"	·1885	"	20·90	·215	"	
"	"	"	·1258	"	28·50	·160	"	
·210	2·32	2·18	·3750	5·00	4·25	1·18	1·4	
"	"	"	·3125	"	4·47	1·12	"	
"	"	"	·2810	"	4·63	1·08	"	
"	"	"	·2500	"	4·56?	?	"	
"	"	"	·1885	"	4·78	1·05	"	
"	"	"	·1258	"	5·50	·91	"	
·186	2·24	2·11	1·31	5·00	3·80	1·67	1·6	Glass. Sp.G. 2·7 rolling on Glass
"	"	"	1·01	"	3·31	1·51	"	
"	"	"	·96	"	3·44	1·45	"	
"	"	"	·76	"	3·80	1·32	"	
"	"	"	·64	"	3·67	1·36	"	

Ht	Vt	Vw.	Db	L	T	Vb	Sp.G in tube C	Remarks.
·031	1·11	1·04	1·31	5·00	8·25	·60	1·6	Glass rolling on Glass. Sp. G 2·7.
"	"	"	1·01	"	8·60	·58	"	
"	"	"	·96	"	8·52	·59	"	
"	"	"	·76	"	9·09	·55	"	
"	"	"	·64	"	9·40	·53	"	
·064	1·57	1·48	1·31	5·00	5·25	·95	1·6	
"	"	"	1·01	"	5·40	·92	"	
"	"	"	·96	"	5·50	·91	"	
"	"	"	·76	"	5·70	·88	"	
"	"	"	·64	"	5·75	·87	"	
·090	1·87	1·76	1·31	5·00	4·29	1·17	1·6	
"	"	"	1·01	"	4·67	1·07	"	
"	"	"	·96	"	4·75	1·05	"	
"	"	"	·76	"	4·95	1·01	"	
"	"	"	·64	"	4·80	1·07	"	
·069	1·38	1·30	1·30	4·00	5·60	·72	1·4	Lead rolling on Glass. Sp. G 11·3.
"	"	"	1·00	"	6·40	·63	"	
"	"	"	·86	"	7·07	·56	"	
"	"	"	·82	"	7·00	·57	"	
"	"	"	·64	"	7·40	·54	"	
·108	1·72	1·60	1·30	4·00	4·80	·83	1·4	
"	"	"	1·00	"	5·00	·80	"	
"	"	"	·86	"	5·17	·77	"	
"	"	"	·82	"	5·17	·77	"	
"	"	"	·64	"	5·71	·70	"	
·130	1·88	1·77	1·30	4·00	4·50	·89	1·4	
"	"	"	1·00	"	4·62	·86	"	
"	"	"	·86	"	4·80	·83	"	
"	"	"	·82	"	4·96	·80	"	
"	"	"	·64	"	5·13	·78	"	
·262	2·63	2·47	1·30	4·00	2·96	1·35	1·4	
"	"	"	1·00	"	3·25	1·23	"	
"	"	"	·86	"	3·33	1·20	"	
"	"	"	·82	"	3·41	1·17	"	
"	"	"	·64	"	3·91	1·02	"	

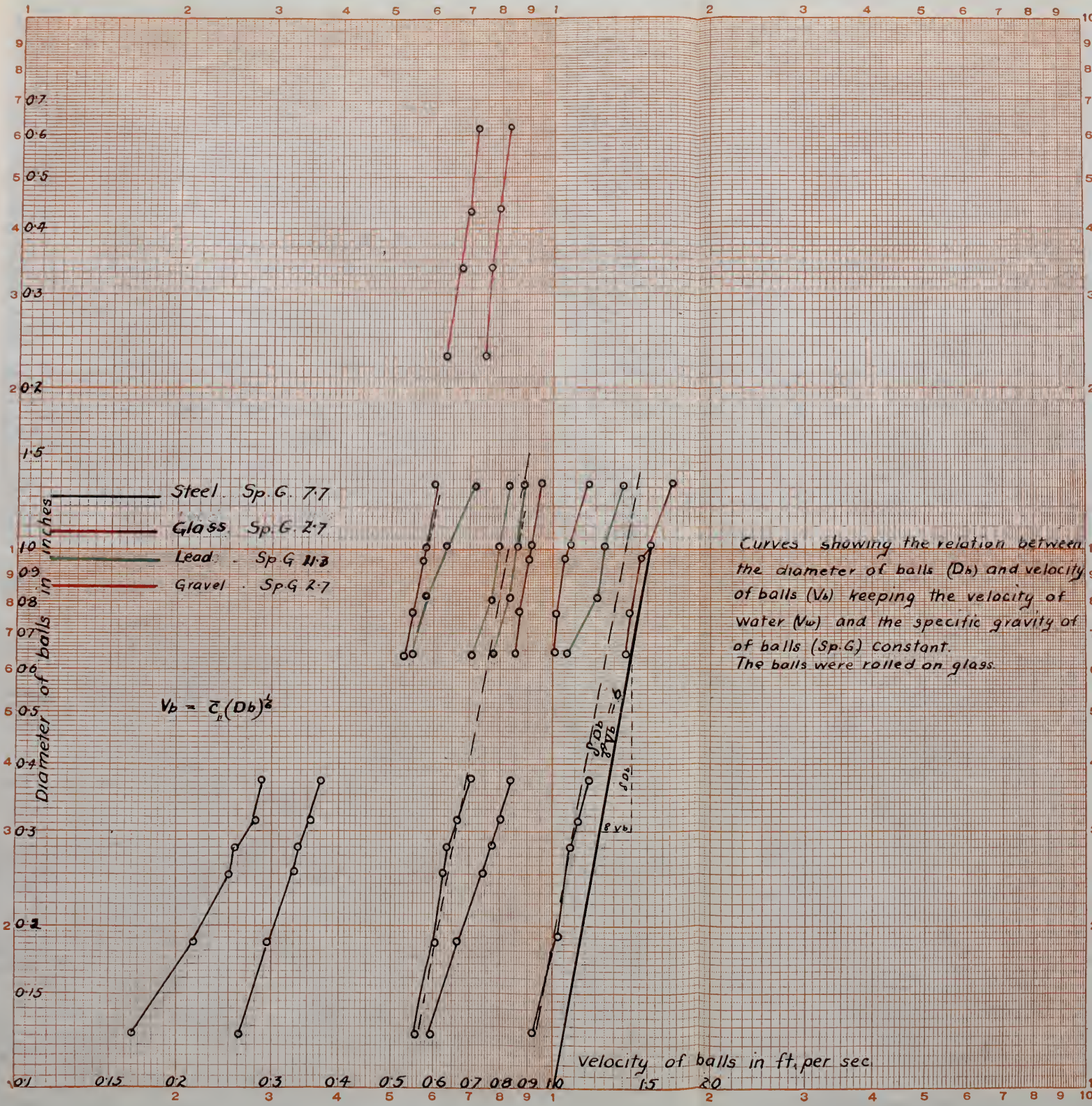
Ht.	Vt.	Vw.	Db.	L	T	Vb	Sp.G in tube C	Remarks
·122	1·82	1·74	·625	5	7·10	·705	1·4	Gravel rolling on Glass. Sp.G 2·7
"	"	"	·437	"	7·37	·680	"	
"	"	"	·338	"	7·40	·675	"	
"	"	"	·230	"	7·94	·630	"	
·185	2·23	2·10	·625	5	6·00	·822	1·4	
"	"	"	·437	"	6·15	·800	"	
"	"	"	·338	"	6·66	·750	"	
"	"	"	·230	"	6·60	·750	"	



Diameter of balls in inches
0·7
0·6
0·5
0·4
0·3
0·2
1·5
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·15
0·1
0·15
0·2
Vb =

arks

Sp·G 7·7

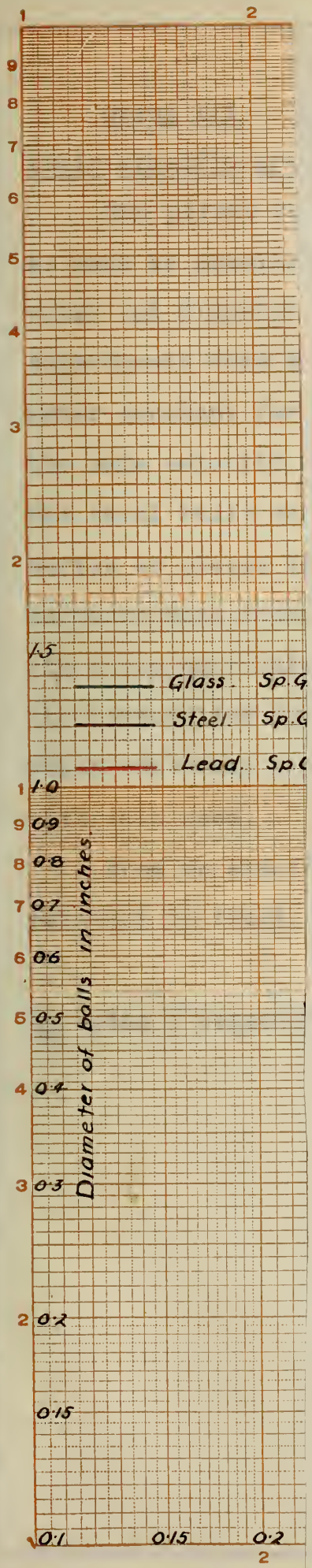


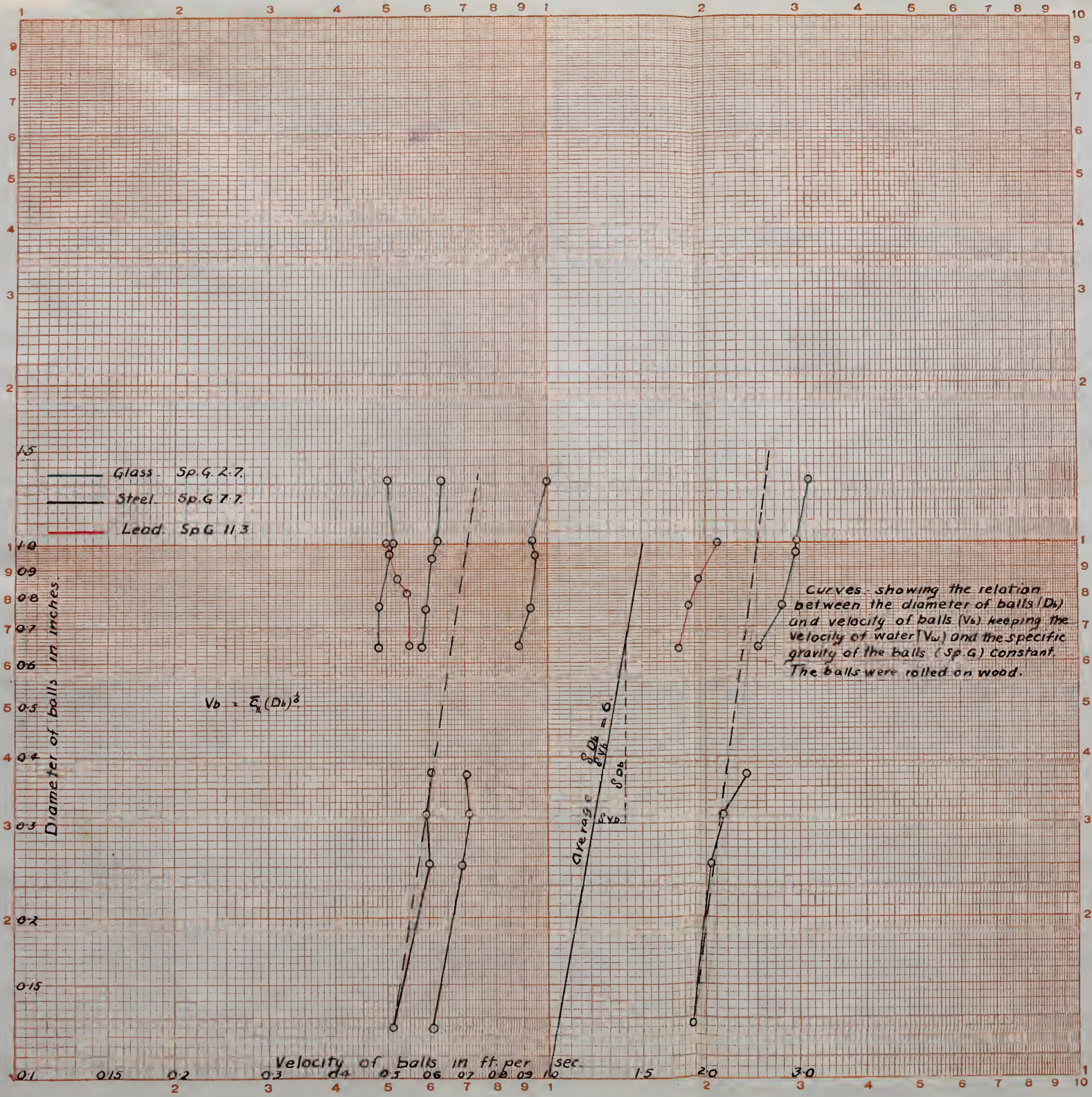
Curves showing the relation between the diameter of balls (D_b) and velocity of balls (V_b) keeping the velocity of water (V_w) and the specific gravity of of balls (Sp.G) constant.
The balls were rolled on glass.

COPYRIGHT 1908. J. NORMAN JENSEN, CIVIL ENGINEER, CHICAGO, ILL., U. S. A.

Ht	Vt	Vw.	Db	L	T	Vb	Sp.G in tube C.	Remarks
·081	1·20	1·13	1·31	5·00	10·03	·50	1·2	Glass rolling on wood Sp.G 2·7
"	"	"	1·01	"	9·90	·51	"	
"	"	"	·96	"	10·00	·50	"	
"	"	"	·76	"	10·50	·48	"	
"	"	"	·64	"	10·50	·48	"	
·235	2·44	2·34	1·31	5·00	5·00	1·00	1·4	
"	"	"	1·01	"	5·30	·94	"	
"	"	"	·96	"	5·20	·96	"	
"	"	"	·76	"	5·40	·93	"	
"	"	"	·64	"	5·60	·89	"	
·105	1·66	1·56	1·31	5·00	7·90	·63	1·4	
"	"	"	1·01	"	8·03	·62	"	
"	"	"	·96	"	8·30	·60	"	
"	"	"	·76	"	8·50	·59	"	
"	"	"	·64	"	8·80	·57	"	
·500	6·21	5·85	1·31	5·00	1·60	3·12	1·6	
"	"	"	1·01	"	1·70	2·94	"	
"	"	"	·96	"	1·70	2·94	"	
"	"	"	·76	"	1·80	2·78	"	
"	"	"	·64	"	2·00	2·50	"	
·219	2·39	2·26	·3750	5·00	8·30	·60	1·4	Steel rolling on wood Sp.G 7·7
"	"	"	·3125	"	8·50	·59	"	
"	"	"	·2500	"	8·40	·60	"	
"	"	"	·1258	"	9·80	·51	"	
·325	2·92	2·74	·3750	5·00	7·20	·70	1·4	
"	"	"	·3125	"	7·10	·71	"	
"	"	"	·2500	"	7·20	·70	"	
"	"	"	·1258	"	8·20	·61	"	
·500	6·21	5·85	·3750	5·00	2·40	2·38	1·6	
"	"	"	·3125	"	2·50	2·14	"	
"	"	"	·2500	"	2·60	2·08	"	
"	"	"	·1258	"	2·70	1·87	"	

Ht	Vt	Vw	Db	L	T	Vb	Sp.G in tube C.	Remarks.
·218	2·39	2·26	1·00	5·00	9·8	·51	1·4	Lead rolling on wood Sp.G.11·3
"	"	"	·86	"	9·7	·52	"	
"	"	"	·82	"	9·3	·54	"	
"	"	"	·64	"	9·0	·55	"	
·600	6·21	5·85	1·00	5·00	2·4	2·10	1·6	
"	"	"	·86	"	2·6	1·92	"	
"	"	"	·82	"	2·7	1·85	"	
"	"	"	·64	"	2·8	1·78	"	


Glass Sp.G
Steel Sp.G
Lead Sp.G
Diameter of balls in inches.
1.5
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.15
0.1
0.15
0.2



COPYRIGHT 1908. J. NORMAN JENSEN, CIVIL ENGINEER, CHICAGO, ILL., U. S. A.

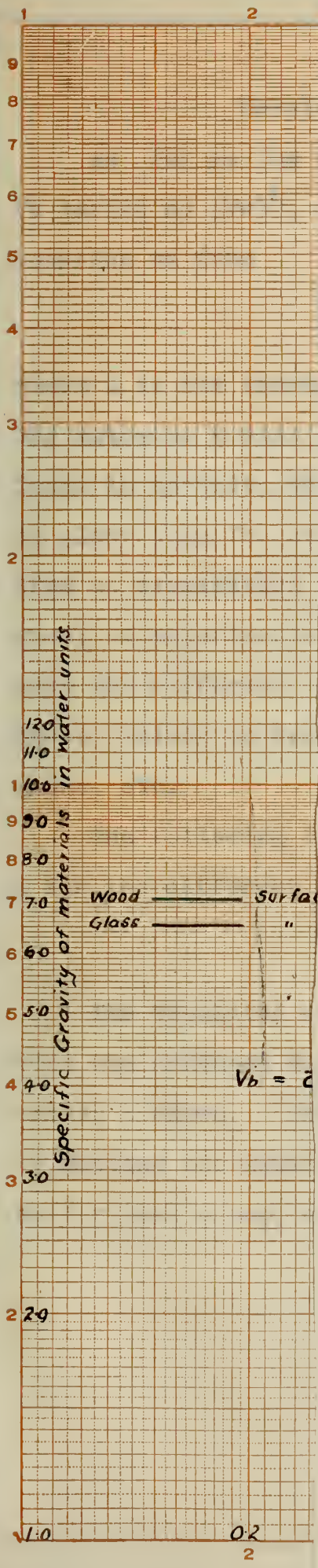
Group III. Relation between the velocity of balls and their specific gravity.

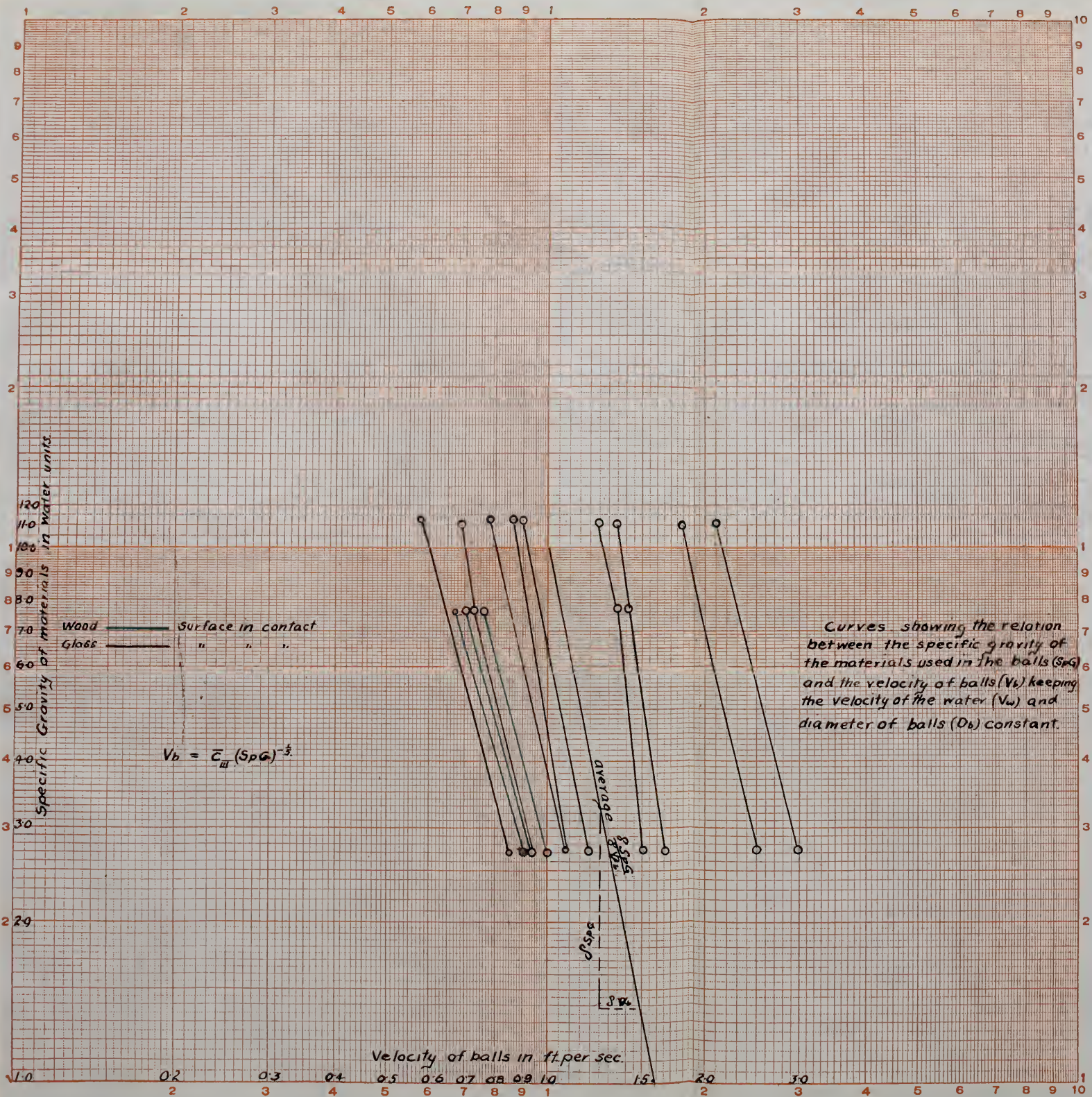
The points on the following logarithmic curves were taken as much as possible from the data sheets. The velocity of the water and diameter of the balls should be constant but since the experiments were not at first performed with the velocity of the water constant for each group, the data where the water approached the same velocity was taken and plotted. Where the diameter of the steel balls were much smaller than that of lead and glass the curves on plates III and IV were produced in order to get a corresponding diameter of ball, to obtain the relationship for the three materials used. These curves produced are shown by the dotted line on these plates and are for velocities of water which come very close in value to that for each of the other materials used.

From an examination of the logarithmic curves the following relation is found,

$$Vb = \overline{C}_{\underline{III}} (SpG)^{-\frac{1}{3}}$$

$\overline{C}_{\underline{III}}$ being a constant.


Specific Gravity of materials in water units
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.2
Wood
Glass
Vb = 2



COPYRIGHT 1908. J. NORMAN JENSEN, CIVIL ENGINEER, CHICAGO, ILL., U. S. A.

Development of Formula.

As far as the experimental work has developed we find that Vb varies as $(Vw)^{\frac{4}{5}}$, $(Db)^{\frac{1}{6}}$ and $(Spec.G)^{-\frac{1}{5}}$ Putting this into an equation we find

$$Vb = \frac{K\ (Vw)^{\frac{4}{5}}(Db)^{\frac{1}{6}}}{(SpG)^{\frac{1}{5}}}$$

where K is the constant that will satisfy the general equation. The value of K will be determined by the character of the surfaces in contact, that is, it will be different for lead rolling on glass than for steel rolling on glass as may be readily seen from an examination of the experimental curves. Therefore each group of experiments has been subdivided into sets which deal with the different values for the constant K, for instance glass rolling on wood has been separated from glass rolling on glass, etc.

The following tables have been prepared in order to obtain K for the different sets in each group of experiments where

$$K = \frac{(SpG)^{\frac{1}{5}}Vb}{(Vw)^{\frac{4}{5}}\ (Db)^{\frac{1}{6}}}$$

The tabulated data was taken from the experimental tabulation and arranged with only the necessary values in order to obtain K shown. The constant $\overline{K}$ for each group was obtained by getting the square root of the average squares of all the Ks for that group, as will be noted in the following tables.

Data and Computations for Determining K.

Vb	Vw.	Db	Sp.G	$Vw.^{\frac{4}{3}}$	$Db^{\frac{1}{2}}$.	$Sp\,G^{\frac{1}{2}}$.	K.	
·700	1·43	·3750	7·7	1·61.	·849	1·50	·768	Steel rolling on Glass.
·833	1·68	"	"	2·00.	"	"	·731	
·370	·90	"	"	·865.	"	"	·764	
·285	·75	"	"	·685.	"	"	·735	
1·18	2·18	"	"	2·83.	"	"	·740	
·665	1·43	·3125	7·7	1·61	·825	1·50	·755	
·805	1·68	"	"	2·00	"	"	·731	
·353	·90	"	"	·865	"	"	·742	
·282	·75	"	"	·685	"	"	·748	
1·12	2·18	"	"	2·83	"	"	·720	
·636	1·43	·2810	7·7	1·61.	·810	1·50	·733	$\sqrt{\text{Average } K^2} = ·711.$
·770	1·68	"	"	2·00.	"	"	·713	
·334	·90	"	"	·865.	"	"	·715	
·264	·75	"	"	·685.	"	"	·715	
1·08	2·18	"	"	2·83.	"	"	·708	
·624	1·43.	·2500	7·7	1·61.	·790	1·50	·736.	
·740	1·68.	"	"	2·00.	"	"	·704.	
·330	·90.	"	"	·865.	"	"	·725.	
·260	·75.	"	"	·685.	"	"	·722.	
1·08.	2·18.	"	"	2·83.	"	"	·725.	
·613.	1·43	·1885	7·7	1·61	·757	1·50	·755	
·666.	1·68	"	"	2·00	"	"	·660	
·294.	·90	"	"	·865	"	"	·702	
·215.	·75	"	"	·685	"	"	·625	
1·045.	2·18	"	"	2·83.	"	"	·730	
·55	1·43	·1258	7·7	1·61	·707	1·50	·725	
·59	1·68	"	"	2·00	"	"	·630.	
·26	·90	"	"	·865	"	"	·637.	
·16	·75	"	"	·685	"	"	·500.	
·91	2·18	"	"	2·83.	"	"	·68.	
1·67.	2·11.	1·31	2·7	2·71	1·045	1·22	·720.	
·606.	1·04.	"	"	1·06	"	"	·670.	
·95.	1·48.	"	"	1·70	"	"	·655.	
1·17.	1·76.	"	"	2·13	"	"	·702.	

Vb	Vw	Db	Sp. G	$Vw^{\frac{4}{3}}$	$Db^{\frac{1}{2}}$	$SpG^{\frac{1}{3}}$	K.	
1·51.	2·11	1·01	2·7	2·71	1·00	1·22	·68.	$\sqrt{\text{Average } K^2} = \cdot 66$ Glass rolling on Glass.
·58.	1·04	"	"	1·06	"	"	·67.	
·92.	1·48	"	"	1·70	"	"	·61.	
1·07.	1·76	"	"	2·13	"	"	·62.	
1·45.	2·11	·96	2·7	2·71	·993	1·22	·66	
·59.	1·04	"	"	1·06	"	"	·68	
·91.	1·48	"	"	1·70	"	"	·66	
1·05.	1·76	"	"	2·13	"	"	·61	
1·42.	2·11	·76	2·7	2·71	·955	1·22	·67	
·55.	1·04	"	"	1·06	"	"	·66.	
·88.	1·48	"	"	1·70	"	"	·66.	
1·01.	1·76	"	"	2·13	"	"	·61.	
1·36.	2·11	·64.	2·7	2·71	·928	1·22	·66	
·53.	1·04	"	"	1·06	"	"	·66.	
·87.	1·48	"	"	1·70	"	"	·67.	
1·07.	1·76	"	"	2·13	"	"	·66.	
·72.	1·30	1·3	11·3	1·42	1·05	1·61	·77	$\sqrt{\text{Average } K^2} = \cdot 648$ Lead rolling on Glass.
·83.	1·60	"	11·3	1·87	"	"	·68	
·89.	1·77	"	11·3	2·14	"	"	·64	
1·35.	2·46	"	11·3	3·34	"	"	·62	
·63.	1·30	1·0	11·3	1·42	1·00	1·61	·71	
·80.	1·60	"	"	1·87	"	"	·69.	
·86.	1·77	"	"	2·14	"	"	·65.	
1·23.	2·47.	"	"	3·34	"	"	·59.	
·56	1·30.	·86	11·3	1·42	·98	1·61	·65.	
·77	1·60.	"	"	1·87	"	"	·68.	
·83	1·77.	"	"	2·14	"	"	·64.	
1·20	2·46.	"	"	3·34	"	"	·60.	
·57	1·30.	·82	11·3	1·42	·97	1·61	·67.	
·77	1·60.	"	"	1·87	"	"	·68.	
80	1·77.	"	"	2·14	"	"	·62.	
1·17	2·46.	"	"	3·34	"	"	·58.	

V_b	V_w	D_b	Sp G	$V_w^{\frac{4}{3}}$	$D_b^{\frac{1}{2}}$	$Sp G^{\frac{1}{3}}$	K.	
·54	1·30	·64	11·3	1·42	·93	1·61	·66.	
·70	1·60	"	"	1·87	"	"	·65.	
·78	1·77	"	"	2·14	"	"	·63.	
1·02	2·47	"	"	3·34	"	"	·53.	
·705	1·74.	·625	2·7	2·09.	·925	1·22	·45.	$\sqrt{\text{Average } K^2} = \cdot 44.$ Gravel rolling on Glass.
·822	2·10.	"	"	2·69.	"	"	·41.	
·680	1·74.	·437	2·7	2·09.	·871	1·22	·45.	
·800	2·10.	"	"	2·69.	"	"	·42.	
·675	1·74.	·338	2·7	2·09.	·835	1·22	·47.	
·750	2·10.	"	"	2·69.	"	"	·41.	
·630	1·74.	·230	2·7	2·09.	·783	1·22	·47.	
·750	2·10.	"	"	2·69.	"	"	·45.	
·50	1·13.	1·31	2·7	1·18.	1·045.	1·22	·49.	$\sqrt{\text{Average } K^2} = \cdot 369.$ Glass rolling on wood.
1·00	2·34.	"	"	3·11.	"	"	·38.	
·63	1·56.	"	"	1·81.	"	"	·41.	
3·12	5·85.	"	"	10·50.	"	"	·35.	
·51.	1·13.	1·01	2·7	1·18.	1·000.	1·22	·53.	
·94.	2·34.	"	"	3·11.	"	"	·37.	
·62.	1·56.	"	"	1·81.	"	"	·42.	
2·94.	5·85.	"	"	10·50.	"	"	·34.	
·48.	1·13.	·76	2·7	1·18.	·955.	1·22	·52.	
·93.	2·34.	"	"	3·11.	"	"	·38.	
·59.	1·56.	"	"	1·81.	"	"	·42.	
2·78.	5·85.	"	"	10·5.	"	"	·34.	
·48.	1·13.	·64	2·7	1·18.	·928	1·22	·53	
·89.	2·34.	"	"	3·11.	"	"	·38	
·57.	1·56.	"	"	1·81.	"	"	·42	
2·50	5·85.	"	"	10·5.	"	"	·31	
·50	1·13.	·96	2·7	1·18.	·993.	1·22	·52.	
·96	2·34.	"	"	3·11.	"	"	·38.	
·60	1·56	"	"	1·81.	"	"	·41.	
2·94	5·85.	"	"	10·5.	"	"	·34.	

V_b.	V_w.	D_b.	Sp.G	$V_w^{\frac{4}{3}}$	$D_b^{\frac{1}{2}}$	$SpG^{\frac{1}{2}}$.	K.	
·60.	2·26.	·3750.	7·7	2·97.	·849	1·50	·36	$\sqrt{\text{Average } K^2} = \cdot 36$ Steel rolling on wood.
·70.	2·74.	"	"	3·83.	"	"	·32.	
2·38.	5·85.	"	"	10·8.	"	"	·39.	
·59.	2·26.	·3125.	7·7	2·97.	8·25	1·50	·36.	
·71.	2·74.	"	"	3·83.	"	"	·34.	
2·14.	5·85.	"	"	10·8.	"	"	·36.	
·60	2·26.	·2500	7·7	2·97.	7·90	1·50	·38.	
·70	2·74.	"	"	3·83.	"	"	·35.	
2·08	5·85.	"	"	10·8.	"	"	·38.	
·51.	2·26.	·1258	7·7	2·97.	7·07	1·50	·36.	
·61.	2·74.	"	"	3·83.	"	"	·34.	
1·87.	5·85.	"	"	10·8.	"	"	·37.	
·51.	2·26.	1·00	11·3	2·97	1·00.	1·61	·28.	$\sqrt{\text{Average } K^2} = \cdot 296.$ Lead rolling on wood.
2·10.	5·85.	"	"	10·8	"	"	·30.	
·52.	2·26.	·86	11·3	2·97	·975.	1·61	·29.	
1·92.	5·85.	"	"	10·8	"	"	·29.	
·54.	2·26.	·82	11·3	2·97	·967	1·61	·30.	
1·85.	5·85.	"	"	10·8	"	"	·29.	
·55.	2·26.	·64	11·3	2·97	·928	1·61	·32.	
1·78.	5·85.	"	"	10·8	"	"	·29.	

The forgoing data show that $\overline{K}$ will vary considerable for the different groups, but is fairly uniform for all values within the group.

$\overline{K}$ as has been mentioned is the constant necessary to satisfy the equation for each group, where the surfaces in contact are the same. It is also necessary to divide $\overline{K}$ in such a way that will give a coefficient for each surface in contact. In order to do this the following method has been adopted. The constant obtained when the glass balls were rolled on glass was taken and the square root obtained in order to get the coefficient for glass. When the surfaces in contact were glass and steel, the coefficient for the steel was obtained by dividing the constant $\overline{K}$ for those surfaces in contact, by the coefficient for glass obtained in the first explanation. This was repeated for each material used and the coefficient thus obtained taken to represent the relative roughness of the surfaces. The rougher the surfaces the smaller will be the numerical value of the coefficients.

Tabulation of constants $\overline{K}$.

For two glass surfaces	$\overline{K}$ = .660	Coef. for glass = .8124
For glass and lead surfaces	$\overline{K}$ = .648	Coef. for lead = .797
For glass and polished steel surfaces	$\overline{K}$ = .711	Coef. for steel = .877
For glass and gravel sur.	$\overline{K}$ = .44	Coef. for gravel = .542
For glass and wood surfaces	$\overline{K}$ = .369	Coef. for wood = .455
For steel and wood surfaces	$\overline{K}$ = .360	Coef. for wood = .410
For lead and wood surfaces	$\overline{K}$ = .296	Coef. for lead = .722

Average Coefficient for wood = .433

Average Coefficient for glass = .812

Average Coefficient for steel = .877

Average Coefficient for lead = .760

Average Coefficient for gravel = .542

Conclusion

The results of the experiments indicate that a definite relationship exists between the velocity of flow and the amount of sediment which can be carried. The effect of the specific gravity of the material was also brought out.

The work carried out was intended mearly as a preliminary survey of this field.For this reason the experiments were made on smooth spherical bodies and very little work was done with irregular bodies such as make up the usual materials carried by streams.The range of velocity was small;it is therefore probable that the experimental laws determined from these experiments will need modification when experiments are mabe including higher velocities of flow. The writer is confident that further research along this line will lead to valuable and definite knowledge,not only as to the transporting capacity of water,but also as to the effect of the velocity of water on bridge piers and embankments.

UNIVERSITY OF ILLINOIS-URBANA
3 0112 082197150